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IMPLICATIONS OF GROUNDWATER HYDROLOGY TO BUFFER DESIGNS IN THE SOUTHEASTERN U.S.

Ge Sun[1], James M. Vose[2], Devendra M. Amatya[3], Carl Trettin[3], and Steven G. McNulty[1]

ABSTRACT: The objective of this study was to examine the hydrologic processes of shallow groundwater to better define and design forest riparian management zones in headwater streams of two contrasting terrains in the southeastern U.S. We employed two long-term experimental watersheds, WS80 (206 ha) and WS77 (151 ha) at the Santee Experimental Forests in South Carolina, and WS2 (12 h) at the Coweeta Hydrologic Lab in the southern Appalachians in North Carolina. These two separate research sites represent a low-gradient and a steep mountain terrain, respectively. Groundwater table monitoring (bi-weekly) over three years (1992-1994) at the two low-gradient watersheds suggest that the temporal water table variability is extremely high for most of the 84 wells while the spatial variability is smaller (<0.5 m). These two watersheds periodically had saturated areas a water level less than 30 cm extending much farther than the stream riparian zones. On average, 23.0% of wells in WS80 and WS77 were saturated during the 122 visits. In contrast, only one of the nine wells located in the zero-order streams showed brief saturation during storms at the mountain watershed over a three-year monitoring period (2005-2007). We found that coastal plain watersheds that received variable rainfalls and had high evapotranspiration (ET) rates had highly variable flow patterns (i.e., either very dry or wet). In contrast, Coweeta watershed (WS2) that received high rainfall but lower ET, had year-round continuous flows. The source of stormflows at the low-gradient watersheds was saturation-excess overland flows that often extended beyond the riparian zones. In contrast, subsurface quick flows dominated the stormflows in Coweeta WS2 that has a narrowly confined riparian zone with saturated areas along the 1st order stream channel. We argue that the existing forestry Best Management Practices (BMP) rules on buffer width developed from upland watershed studies may not be adequate in protecting water quality for the low-gradient coastal watersheds. Overland flow in steep upland watersheds rarely occurs, thus attention should be focused on managing subsurface flows and stream bank protections.

INTRODUCTION

Forest riparian buffers offer important water quality benefits through the physical, chemical, biological interactions between the upland runoff and vegetation, soil, and the rich micro- and macro-organisms in the buffers (Pru'dhomme and Greis, 2002). Thus, all forestry BMP prescriptions list buffers (also called Streamside Management Zones, SMZs) as one of the key principles to reduce negative impacts from forests activities such as harvesting, fertilization, road building etc (Olzewski and Jackson, 2006). In most southeastern States, the minimum buffer width is prescribed as a function of magnitude of upland disturbances, upland slopes, and the size and type of streams (perennial, intermittent, or ephemeral) to be protected. For example, depending on whether the streams support trout, and the type of streams and upland slopes, the forest buffer widths can vary from 40 feet (12.2 m) to 200 feet (61 m) in South Carolina. However, the 2006 North Carolina Forestry BMPs require a 40 feet buffer regardless of slopes and stream characteristics in most cases. The manual suggested that the recommendations are still best guess/best judgment (Technical Advisory Committee, NC DENR-Division of Forest Resources). The buffer designs have important economic implications to landowners. William and Cubbage (1994) estimated that BMP compliance costs $24-$41 per acre for private forest owners. The currently adopted BMPs manuals are a product of consensus and do not necessarily reflect the science or scientifically prescribed norms.

Rainfall intensity rarely exceeds infiltration capacity of forest soils, thus Hortonian overland flows are not common in undisturbed forest lands including the forest riparian areas. However, saturation-excess overland flows do occur when the soils are fully saturated and the shallow groundwater table reaches the ground surface (Riekerk, 1989; Sun et al., 2002). This type of overland flow is common in the low land watersheds and the near-stream riparian areas in upland watersheds. The riparian areas, termed as the 'variable sources' in modern forest hydrology are the sources of storm flow (Hewlett and

[1] Respectively, Research Hydrologist, Research Ecologist and Team Leader, USDA Forest Service, 920 Main Campus Drive Suite 300, Raleigh, NC 27606, Phone: (919) 515-9498, Fax: (919) 513-2978, Email: ge_sun@ncsu.edu

[2] Research Ecologist, Coweeta Hydrologic Lab, USDA Forest Service, Otto, NC;

[3] Respectively, Research Hydrologist, Team Leader, Center for Forested Wetlands Research, USDA Forest Service, 3734 Highway 402, Cordesville, SC 29434

Hibbert, 1967; Dune and Black, 1970). Thus, the variable source areas are often regarded as 'hot spot' critical zones in controlling non-point source pollution. Shallow groundwater and saturation overland flows are the major hydraulic linkage between streams and uplands in headwater forested watersheds. Thus, designing the appropriate size of forest buffers to protect water quality requires quantitative information of the groundwater hydrologic processes of the riparian zones. The Variable Source Area Concept (VSAC) developed in the 1960s has been widely accepted as the scientific basis for designing forest buffers in spite of its limitation in explaining the stormflow generation mechanisms for certain landscapes (Sidle et al., 2000). The actual sizes of variable source areas have been rarely quantified due to their dynamic nature and limitations of instrumentation in the past. Consequently, in practice, the design of forest buffers for water quality protection purposes is rather subjective from the hydrologic point of view. Understanding the flow paths and tracking the sources of storm flow is important to improve existing watershed-scale hydrologic models for water quality management (Burgess et al., 1988).

The objective of this study was to describe the hydrologic processes in two contrasting landscapes, one located in the low lands of South Carolina and one in the steep mountainous western North Carolina using the available groundwater flow data. Our goal was to better define and design forest riparian buffer (SMZs) within the southeastern region. We hypothesized that the two types of watersheds with different topographic conditions have two different storm flow generation mechanisms and buffer designs should reflect these differences. Also, we hypothesized that the shallow groundwater flow plays an important role in flow generation mechanism in both upland and lowland forested watersheds.

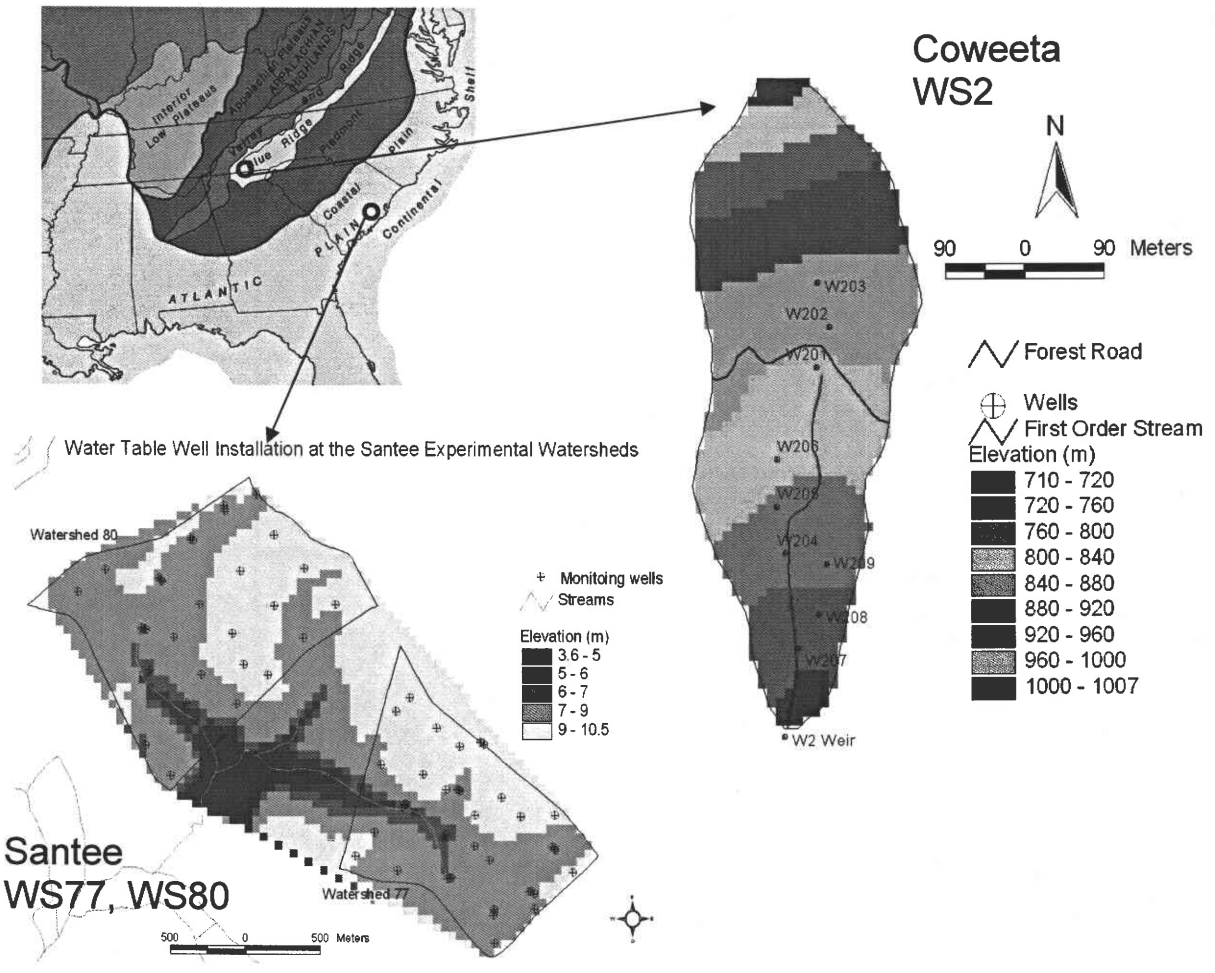

Figure 1. Field installations for shallow groundwater table measurements at two contrasting research sites.

METHODS

This study was conducted in three small headwater watersheds located in two separate experimental forests in the southeastern U.S. (Figure 1). The first watershed, WS2 (12 ha), is located at the Coweeta Hydrology Laboratory in western North Carolina, representing a steep landscape in the southern Appalachian mountain geographic region (Table 1). The other two watersheds, WS80 and WS77 are located at the Santee Experimental Forest in South Carolina, representing a low-gradient landscape on the Atlantic coastal plain. At WS2, nine pressure transducers were installed in three 200-m transects located in three concave/intermittent zero order streams (Figure 1). The shallow groundwater tables in the nine wells were continuously recorded every 15 minutes from March 2005 to April 2008. Streamflow was measured at the watershed outlet and climate variables were recorded at a nearby weather station (Amatya et al., 2006). At WS80 and WS77, over 80 shallow manual wells were used to measure groundwater table depths at a bi-weekly schedule during 1992-1994. The ESRI ArcView software was used for spatial display and analysis of water table frequency distribution and its relations to the distance from the wells to the nearest stream. Regression analysis between water table depth and stream flow at WS2 was performed with the SAS software (SAS version 9.2).

Table 1 Physical and Climatic Characteristics of the Three Experimental Watersheds

Location	Watershed	Area (ha)	Elevation (m)	Vegetation	Soils	Climate	Slope	Average runoff ratio
Coweeta Hydrologic Laboratory, NC	WS2	12	710-1007	Deciduous hardwoods	Sandy loam	Average annual precipitation = 1770 mm Potential Evapotranspiration = 820 mm (Hamon method)	43%	~48%
Santee Experimental Forests, SC	WS80 (Control watershed)	206	3.6-10.5	Regenerated mixed pine-hardwoods	Sandy loam	Average annual precipitation = 1396 mm/yr Grass reference Evapotranspiration (2003-2006) = 950 mm	<4%	~ 22%
	WS77 (harvested in 1990 after hurricane damage in 1989)	151	5-10.5					~ 27%

RESULTS AND DISCUSSION

Water Table Dynamics at the Upland Watershed, WS2

This study covered three years with different rainfall patterns. The annual rainfall of 2005 was 2142 mm, highest in the 60-year record at Coweeta. Year 2006 had a below-average precipitation of 1630 mm. The watershed experienced a severe drought in 2007 starting from earlier summer, and ended with an annual rainfall of only 1297 mm or 71% of the long term average.

Among the nine wells installed in the three transects (Figure 1), only five (No1, No5, No7, No8, No9) had a watershed table that fluctuated within 1.5 m from the ground surfaces. The water table rise in Well No1 was measurable only once on 9/25/2006 after several continuous storm events with a total of 42 mm). Recorders in other four wells (No2, No3, No4, No6) were not able to measure water tables at a depths of 1.0-1.9 m. Well No9 could measure the water table during the study period, but the fluctuation was rather small (<8 cm). Only the water tables measured at No8 and No5 did ever almost reach the ground surface (<10 cm) during storm events (Figures 2). The groundwater table measured at Well No8 responded to rainfall events rather quickly and dropped fast as well (Figure 2). This well was installed directly on the 'streambed' of a zero-order watershed. Storm flow patterns appear to follow the water table responses of Well No8 closely, but it did to a much less extent for Well No5. Well No7, which was next to the stream bank, showed little response to rainfall events and the groundwater table never reached the surface. During dry periods, the ground water table at Well No7 was responsive to diurnal evapotranspiration and uphill groundwater recharge. It dropped at day time, but rose at night.

Water Table Dynamics at the Two Low land Watersheds, WS77 and WS80

During the three-year (1992-1994) measurement period, the groundwater table at any location in the two watersheds varied greatly in time. For example, the averaged water table was 17 cm above the ground surface on the wettest date on 8/17/1994 in WS80, but the watershed was extremely dry during May-October of 1993 when the averaged groundwater table was more than 1 m below the ground surface. Due to the low topographic relief, the measured differences among the 80 wells were less than 0.5 m in most measurements. The fully saturated area periodically extended much farther than the stream riparian zones. A total of 122 measurements (times) were made on all manual wells. On average, 22.8% (STDEV=27.3%) and 22.3% (STDEV= 26.3%) of the wells were fully saturated at the surface for WS77 and WS80 (Figure 3), respectively. The frequency of saturation of the measurement locations does not follow the land topographic gradient. There were no significant (α = 0.05) relationships between the shortest distance between a well to the nearest stream and the frequency distribution of the two categories of water table depth (> 0 cm or 0 to -15 cm) at both watersheds (Figure 4).

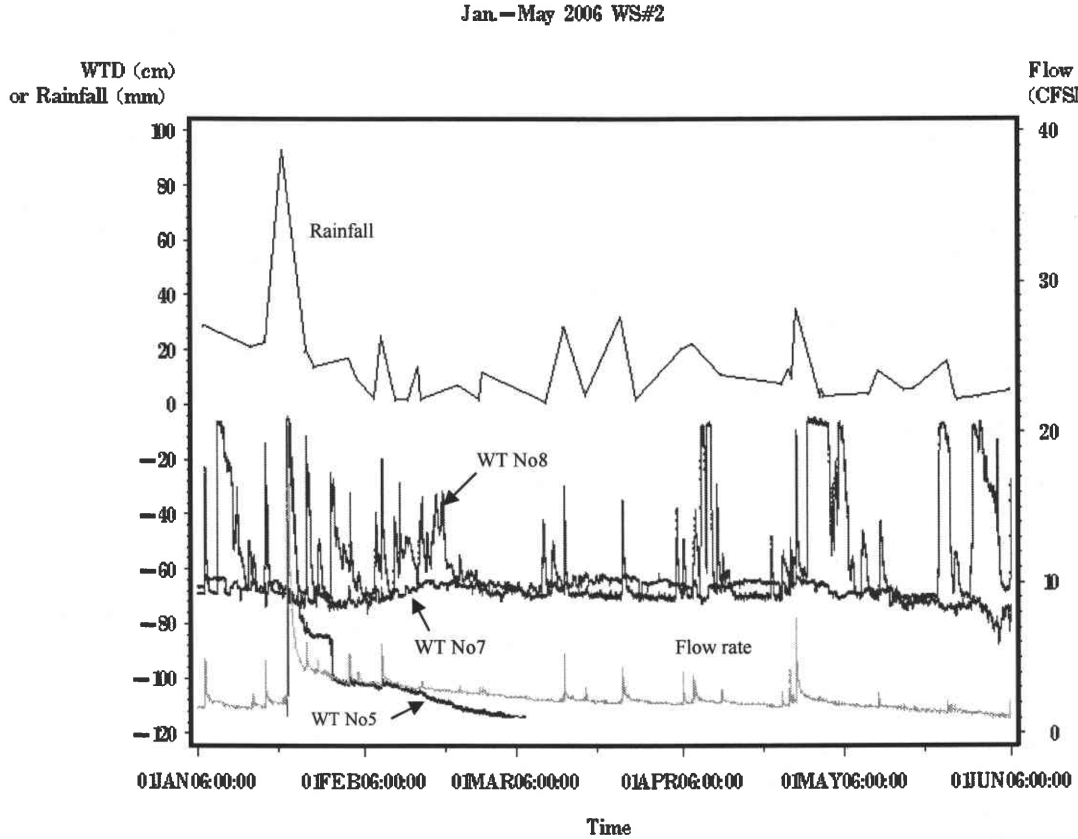

Figure 2. Responses of water table and streamflow to rainfall events during January-May, 2006 showing very different groundwater responses to storm events. Note: Rainfall data show rainfall starting time and total amount.
Three-year (1992-1994) of bi-monthly groundwater table monitoring data from the two Santee watersheds

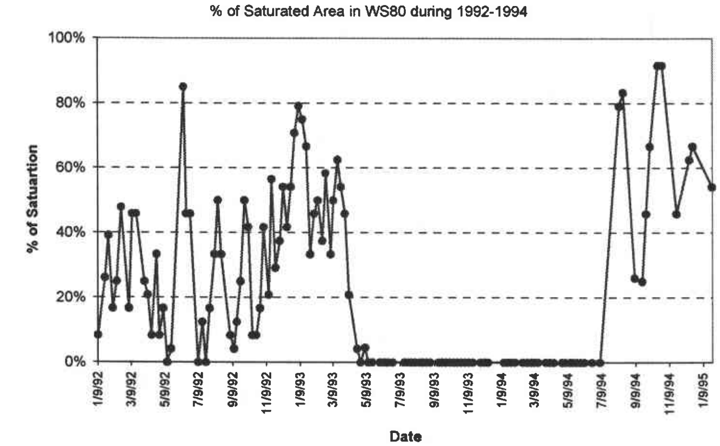

Figure 3. Percentage of wells that were measured with full saturation for each of the bi-weekly visit, showing the dynamics of the variable sources areas in WS80.

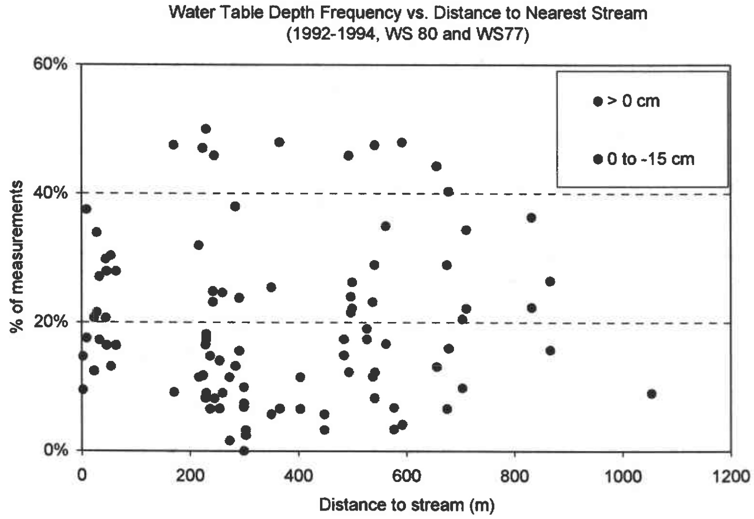

Figure 4 The frequency of saturation or close-to-saturation occurrences does not correlate with the distance from the point of measurements to the nearest streams, suggesting little controls of topography on water table depth.

CONCLUSIONS

This study examined the shallow groundwater table dynamics over three years from different periods in three small contrasting first-order watersheds. The upland watershed that has steep hill slopes and deeply incised stream channels had a perennial stream even during extreme drought conditions. Such headwater streams have very narrow riparian areas where groundwater tables rarely reached the land surfaces even during extreme storm events. Stormflows were generated mostly by fast flowing subsurface flows since saturation-excess overland flows were not common in this heavily forested mountain watershed. High rainfall and relatively low evapotranspiration in the non-growing seasons might explain the large saturated watershed 'volume' (i.e. groundwater thickness).

In contrast, the two coastal plain watersheds with little topographic relief and high evapotranspiration rates have highly variable flow patterns (i.e., either very dry or flooded). The saturated or close-to-saturation areas extended much further than the narrow riparian zones as suggested by most forestry BMPs. Stormflow were mostly generated from the saturated areas during extreme rainfall events when saturation-excess overland flow occurred (Harder et al., 2007).

Little guidance is available on the BMPs buffer design for headwater streams. Based on the groundwater data, two very different mechanisms to explain overland flow and storm flow generation processes were identified. We argue that the existing BMPs on forest buffer width developed for upland watersheds may not be adequate in protecting water quality for the low land coastal watersheds. For the upland watersheds with a narrow riparian zone, overland flow rarely occurs and attention should be focused on managing subsurface flow in hillslopes and zero-order watersheds that produce most of the stormflow. A narrow buffer zone may not cause negative impacts on water quality as long as land surfaces and stream banks are well protected and subsurface flows are not altered. Maintaining the forest evapotranspiration capacity of the riparian zones is also important to protect the groundwater flow pathways and to reduce likelihood of overland flow (Ford and Vose, 2007).

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